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High Voltage Rotating Electric Machines

TECHNICAL FIELD

This invention relates to a rotating electric machine and in particular to a rotating electric machine with at least one magnetic circuit comprising a magnetic core and a winding. Examples of such rotating electric machines to which the invention relates are synchronous machines which are mainly used as generators for connection to distribution and transmission networks, commonly referred to below as "power networks". Other uses of synchronous machines are as motors and for phase compensation and voltage control, e.g. as mechanically idling machines. Other rotating electric machines to which the invention relates are double-fed machines, asynchronous machines, asynchronous converter cascades, outer pole machines and synchronous flux machines.

The magnetic circuit of a rotating electric machine referred to in this context comprises a magnetic core of laminated, normal or oriented, sheet material or other, for example amorphous or powder-based, material, or any other device providing a closed path of alternating magnetic flux. The magnetic circuit may also include a winding, a cooling system, etc., and may be located in the stator of the machine, the rotor of the machine, or in both the stator and the rotor.

BACKGROUND ART

A magnetic circuit of a conventional rotating electric machine in the form of a synchronous machine is, in most cases, located in the stator of the machine. Such a magnetic circuit is normally described as a stator with a laminated core, the winding of which is referred to as a stator winding, and the slots in the laminated core for the winding are referred to as stator slots or simply slots.

Ins. B1

~~Most synchronous machines have a field winding in the~~ rotor, where the main flux is generated by ~~dc, and~~ an ac winding which is in the stator. Synchronous machines are normally of three-phase design and may be designed with salient poles. This latter type of synchronous machine have ~~an ac winding in the rotor.~~

The stator body for a large synchronous machine is often constructed from welded together sheet steel. The laminated core is normally made from varnished 0.35 or 0.5 mm thick laminations. For larger machines, the sheet is punched into segments which are attached to the stator body by means of wedges/dovetails. The laminated core is retained by pressure fingers and pressure plates.

Three different cooling systems are available to cool the windings of the synchronous machine. With air cooling, both the stator winding and the rotor winding are cooled by cooling air flows. Cooling air ducts are provided both in the stator laminations and in the rotor. For radial ventilation and cooling by means of air, the sheet iron core, at least for medium-sized and large machines, is divided into stacks with radial and axial ventilation ducts disposed in the core. The cooling air may consist of ambient air but at powers exceeding 1 MW, a closed cooling system with heat exchangers is often used.

Hydrogen cooling is normally used in turbogenerators up to about 400 MW and in large synchronous condensers. This cooling method functions in a manner similar to air cooling with heat exchangers, but instead of air as coolant, hydrogen gas is used. The hydrogen gas has better cooling capacity than air, but difficulties arise at seals and in monitoring leakage.

For turbogenerators having a power range of 500-1000 MW, it is known to apply water cooling to both the stator winding and the rotor winding. The cooling ducts are in the form of

tubes which are placed inside conductors in the stator winding.

One problem with large machines is that the cooling tends to become non-uniform resulting in temperature differences arising across the machine.

The stator winding is located in slots in the sheet iron core, the slots normally having a rectangular or trapezoidal cross section. Each winding phase comprises a number of coil groups connected in series with each coil group comprising a number of coils connected in series. The different parts of the coil are designated the "coil side" for the part which is placed in the stator and the "end winding" for that part which is located outside the stator. A coil comprises one or more conductors brought together in height and/or width.

Between each conductor or conductor turn of a coil there is a thin insulation, for example epoxy/glass fibre.

The coil is electrically insulated from the slot by coil insulation, that is, an insulation intended to withstand the rated voltage of the machine to earth. As insulating material, various plastics materials, varnish and glass fibre materials are conventionally used. Usually, so-called mica tape is used, which is a mixture of mica and hard plastics material, especially produced to provide resistance to partial discharges, which can rapidly break down the electrical insulation. The insulation is applied to the coil by winding several layers of the mica tape around the coil. The insulation is impregnated, and the coil side is painted with a graphite based paint to improve the contact with the surrounding stator which is connected to earth potential.

The conductor area of the windings is determined by the current intensity in question and by the cooling method used. The conductor and the coil are usually of a rectangular shape to maximise the amount of conductor material in the slot. A

typical coil is formed of so-called Roebel bars, in which some of the bars are made hollow for a coolant. A Roebel bar comprises a plurality of rectangular, copper conductors connected in parallel, which are transposed 360 degrees along the slot. Ringland bars with transpositions of 540 degrees and other transpositions also occur. The transposition is made to avoid the occurrence of circulating currents which are generated in a cross section of the conductor material, as viewed from the magnetic field.

For mechanical and electrical reasons, a machine cannot be made of just any size. The machine power is determined substantially by three factors:

- The conductor area of the windings. At normal operating temperature, copper, for example, has a maximum value of from 3 to 3.5 A/mm^2.

- The maximum flux density (magnetic flux) in the stator and rotor material.

- The maximum electric field strength in the electrical insulation, the so-called dielectric strength.

Polyphase ac windings are designed either as single-layer or two-layer windings. In the case of single-layer windings, there is only one coil side per slot, and in the case of two-layer windings there are two coil sides per slot. Two-layer windings are usually designed as diamond windings, whereas the single-layer windings which are relevant in this connection may be designed as a diamond winding or as a concentric winding. In the case of a diamond winding, only one coil span (or possibly two coil spans) occur, whereas flat windings are designed as concentric windings, that is, with a greatly varying coil span. By "coil span" is meant the distance in circular measure between two coil sides belonging to the same coil, either in relation to the relevant pole pitch or in the number of intermediate slot pitches. Usually,

different variants of chording are used, for example short-pitching, to give the winding the desired properties.

The type of winding substantially describes how the coils in the slots, that is, the coil sides, are connected together outside the stator, that is, at the end windings.

Outside the stacked sheets of the stator, the coil is not provided with a painted semiconducting ground-potential layer. The end winding is normally provided with an E-field control in the form of so-called corona protection varnish intended to convert a radial field into an axial field, which means that the insulation on the end windings occurs at a high potential relative to earth. This sometimes gives rise to corona discharges in the coil-end region, which may be destructive. The so-called field-controlling points at the end windings entail problems for a rotating electric machine.

Normally, all large machines are designed with a two-layer winding and equally large coils. Each coil is placed with one side in one of the layers and the other side in the other layer. This means that all the coils cross each other in the end winding. If more than two layers are used, these crossings render the winding work difficult and deteriorate the end winding.

It is generally known that the connection of a synchronous machine/generator to a power network must be made via a Æ/D-connected so-called step-up transformer, since the voltage of the power network normally lies at a higher level than the voltage of the rotating electric machine. Together with the synchronous machine, this transformer thus constitutes integrated parts of a plant. The transformer constitutes an extra cost and also has the disadvantage that the total efficiency of the system is lowered. If it were possible to manufacture machines for considerably higher voltages, the step-up transformer could thus be omitted.

During the last few decades, there has been an increasing demand for rotating electric machines of higher voltages than it has previously been possible to design. The maximum voltage level which, according to the state of the art, has been possible to achieve for synchronous machines with a good yield in the coil production is around 25-30 kV.

Certain attempts to a new approach as regards the design of synchronous machines are described, inter alia, in an article entitled "Water-and-oil-cooled Turbogenerator TVM-300" in J. Elektrotechnika, No. 1, 1970, pp. 6-8, in US-A-4,429,244 "Stator of Generator" and in Russian patent specification CCCP 955369.

The water- and oil-cooled synchronous machine described in J. Elektrotechnika is intended for voltages up to 20 kV. The article describes a new insulation system consisting of oil/paper insulation, which makes it possible to immerse the stator completely in oil. The oil can then be used as a coolant while at the same time using it as insulation. To prevent oil in the stator from leaking out towards the rotor, a dielectric oil-separating ring is provided at the internal surface of the core. The stator winding is made from conductors with an oval hollow shape provided with oil and paper insulation. The coil sides with their insulation are secured in rectangular section slots by wedges. Oil is used as a coolant both in the hollow conductors and in holes in the stator walls. Such cooling systems, however, require a large number of connections of both oil and electricity at the coil ends. The need for thick insulation also entails an increased radius of curvature of the conductors, which in turn results in an increased size of the winding overhang.

US-A-4,429,244 relates to the stator part of a synchronous machine which comprises a magnetic core of laminated sheet with trapezoidal slots for the stator winding. The slots are tapered because there is less need for electrical insulation of the stator winding towards the rotor

where the part of the winding nearest to the neutral point is located. In addition, the stator part comprises a dielectric oil-separating cylinder nearest the inner surface of the core. This part may increase the magnetization requirement relative to a machine without such a cylinder. The stator winding is made of oil-immersed cables with the same diameter for each coil layer. The layers are separated from each other by means of spacers in the slots and secured by wedges. What is special for the winding is that it comprises two so-called half-windings connected in series. One of the two half-windings is located, centred, inside an insulating sleeve and conductors of the stator winding are cooled by surrounding oil. Disadvantages with such a large quantity of oil in the system are the risk of leakage and the considerable amount of cleaning work which may result from a fault condition. Those parts of the insulating sleeve which are located outside the slots have a cylindrical part and a conical termination reinforced with current-carrying layers, the purpose of which is to control the electric field strength in the region where the cable enters the end winding.

From CCCP 955369 it is clear, in another attempt to raise the rated voltage of the synchronous machine, that the oil-cooled stator winding comprises a conventional high-voltage cable with the same dimensions for all the layers. The cable is placed in stator slots formed as circular, radially located openings corresponding to the cross-sectional area of the cable and the necessary space for fixing and for coolant. The different radially located layers of the winding are surrounded by and fixed in insulating tubes. Insulating spacers fix the tubes in the stator slot. Because of oil cooling, an internal dielectric ring is also needed to seal the oil coolant from the internal air gap. The disadvantages of oil in the system described above also apply to this design. The design also exhibits a very narrow radial waist between the different stator slots, which implies a large slot leakage flux which significantly influences the magnetization requirement of the machine.

A report from Electric Power Research Institute, EPRI, EL-3391, from 1984 describes a review of machine concepts for achieving a higher voltage of a rotating electric machine for the purpose of connecting a machine to a power network without an intermediate transformer. Such a solution is said to provide good efficiency gains and great economic advantages. The main reason for considering in 1984 the development of generators for direct connection to power networks was that at the time a superconducting rotor had been produced. The large magnetization capacity of the superconducting field makes it possible to use an air gap winding with a sufficient insulation thickness to withstand the electrical stresses. By combining the most promising concept, according to the project, of designing a magnetic circuit with a winding, a so-called monolith cylinder armature, a concept where the winding comprises two cylinders of conductors concentrically enclosed in three cylindrical insulating casings and the whole structure being fixed to an iron core without teeth, it was judged that a rotating electric machine for high voltage could be directly connected to a power network. The solution meant that the main insulation had to be made sufficiently thick to cope with network-to-network and network-to-earth potentials. The insulation system which, after a review of all the technique known at the time, was judged to be necessary to manage an increase to a higher voltage was that which is normally used for power transformers and which consists of dielectric-fluid-impregnated cellulose pressboard. Obvious disadvantages with the proposed solution are that it requires a very thick insulation which increases the size of the machine. The end windings must be insulated and cooled with oil or freon to control the large electric fields in the ends. The whole machine must be hermetically enclosed to prevent the liquid dielectric from absorbing moisture from the atmosphere.

During the decades around 1930 a few generators with high voltages up to 36 kV were built in order to develop a generator for direct connection to power networks. One

project was based on using conductors of concentric type, with three layers of conductors enclosed in insulation, where each layer was connected in series and the inner layer was at the highest potential. In another version the electrical conductors were made of twisted copper strips that were isolated with special layers of mica, varnish and paper.

When manufacturing rotating electric machines according to the state of the art, the winding is manufactured with conductors and insulation systems in several steps, whereby the winding must be preformed prior to mounting in the magnetic circuit. Impregnation for preparing the insulation system is performed after mounting of the winding in the magnetic circuit.

SUMMARY OF THE INVENTION

An aim of the present invention is to obtain a rotating electric machine with such a high voltage that the use of a step-up transformer mentioned above can be omitted, that is, machines with a considerably higher voltage than machines according to the state of the art can be connected directly to power networks. This means considerably lower investment costs for systems with a rotating electric machine and the total efficiency of the system can be increased.

The rotating electric machine can be connected to a power network with a minimum of connecting devices such as circuit breakers, disconnectors or the like. In a system with a rotating machine directly connected to a power network without an intermediate transformer the connection can be made using only one circuit breaker.

A further aim of the present invention is to provide an electrical machine having at least one winding including conducting means which have improved electrically conducting properties at low temperatures and cooling means for cooling

the conducting means below normal ambient operating temperatures and preferably to at least 200 K.

According to one aspect of the present invention, there is provided a high voltage rotating electric machine as claimed in the ensuing claim 1.

According to other aspects of the present invention, there is provided a high voltage rotating electric machine as claimed in the ensuing claims 9 and 26.

In use of a rotating electric machine according to the invention there is a considerably reduced thermal stress on the stator and/or rotor. Temporary overloads of the machine thus become less critical and it will be possible to drive the machine at overload for a longer period of time without running the risk of damage arising. This means considerable advantages for owners of power generating plants who are forced presently, in case of operational disturbances, to switch rapidly to other equipment in order to ensure the delivery requirements laid down by law.

With a rotating electric machine according to the invention, maintenance costs can be significantly reduced because transformers and circuit breakers do not have to be included in the system for connecting the machine to the power network.

To increase the power of a rotating electric machine, it is known that the current in the ac coils should be increased. This has been achieved by optimizing the quantity of conducting material, that is, by close-packing of rectangular conductors in the rectangular rotor slots. The aim was to handle the increase in temperature resulting from this by increasing the quantity of insulating material and using more temperature-resistant and hence more expensive insulating materials. The high temperature and field load on the insulation has also caused problems with the life of the

insulation. In the relatively thick-walled insulating layers which are used for high-voltage equipment, for example impregnated layers of mica tape, partial discharges, PD, constitute a serious problem. When manufacturing these insulating layers, cavities, pores, and the like, will easily arise, in which internal corona discharges arise when the insulation is subjected to high electric field strengths. These corona discharges gradually degrade the material and may lead to electric breakdown through the insulation.

The present invention is based on the realisation that, an increase in power of a rotating electrical machine in a technically and economically justifiable way, is achieved by ensuring that the electrical insulation is not broken down by the phenomena described above. This can be achieved by extruding layers of a suitable solid insulating material resulting in the electric field stress being less than 0.2 kV/mm in any gaseous space in or around the electrical insulation. The electrical insulation may be applied in some other way than by extrusion, for example by spraying, figure moulding, compression moulding, injection moulding or the like. It is important, however, that the insulation should have no defects through the whole cross section and should possess similar thermal properties.

Conveniently the electrically insulating intermediate layer comprises solid thermoplastics material, such as low density polyethylene (LDPE), high density polyethylene (HDPE), polypropylene (PP), polybutylene (PB), polymethylpentene (PMP), cross-linked materials, such as cross-linked polyethylene (XLPE), or rubber insulation, such as ethylene propylene rubber (EPR), ethylene butyl acrylate copolymer rubber, an ethylene-propylene-diene monomer rubber (EPDM) or silicone rubber. The semiconducting inner and outer layers may comprise similar material to the intermediate layer but with conducting particles, such as particles of carbon black or soot, embedded therein. Generally it has been found that a particular insulating material, such as EPR, has similar

mechanical properties when containing no, or some, carbon particles.

The semiconducting inner layer is preferably electrically connected to, so as to be at substantially the same electric potential as, the superconducting means.

The semiconducting outer layer is preferably connected to a controlled electric potential, preferably earth potential. Connection to the controlled potential is preferably made at spaced apart locations along the length of the outer layer.

In the present specification the term "semiconducting material" means a material having a considerably lower conductivity than an electric conductor but which does not have such a low conductivity that it is an insulator. For example, the semiconducting inner and outer layers may have a resistivity within the interval 1 to 100 kΩ-cm. By using only insulating layers which may be manufactured with a minimum of defects and, in addition, providing the insulation with an inner and an outer semiconducting layer, it can be ensured that the thermal and electric loads are reduced. The intermediate layer should preferably in close contact with, and preferably be adhered to, the inner and outer layers. Conveniently the various layers are extruded together.

The electrically conducting means preferably comprises superconducting means. In this case the conducting means conveniently comprises central tubular support means for conveying cryogenic coolant fluid, e.g. liquid nitrogen, in which case the superconducting means is of elongate form and is wound around the tubular support means. The superconducting means may comprise low temperature superconductors, but most preferably comprises high-temperature (high-T_c) superconducting (or HTS) materials, for example HTS wires or tape helically wound on the tubular support means. A convenient HTS tape comprises silver-sheathed BSCCO-2212 or

BSCCO-2223 (where the numerals indicate the number of atoms of each element in the $[Bi, Pb]_2\ Sr_2\ Ca_2\ Cu_3\ Ox$ molecule) and hereinafter such HTS tapes will be referred to as "BSCCO tape(s)". BSCCO tapes are made by encasing fine filaments of the oxide superconductor in a silver or silver oxide matrix by a powder-in-tube (PIT) draw, roll, sinter and roll process. Alternatively the tapes may be formed by a surface coating process. In either case the oxide is melted and resolidified as a final process step. Other HTS tapes, such as TiBaCaCuO (TBCCO-1223) and YBaCuO (YBCO-123) have been made by various surface coating or surface deposition techniques. Ideally an HTS wire should have a current density beyond $j_c \sim 10^5$ Acm^{-2} at operation temperatures from 65 K, but preferably above 77 K. The filling factor of HTS material in the matrix needs to be high so that the engineering current density $j_e \geq 10^4$ Acm^{-2}. j_c should not drastically decrease with applied field within the Tesla range. The helically wound HTS tape is cooled to below the critical temperature T_c of the HTS by a cooling fluid, preferably liquid nitrogen, passing through the tubular support means.

The electrically insulating material may be applied directly over the conducting means. Alternatively thermal expansion means may be provided to cater for differences in coefficients of thermal expansion between the conducting means and the electrically insulating material. For example, a space may be provided between the conducting means and the surrounding electrical insulation, the space either being a void space or a space filled with compressible material, such as a highly compressible foamed material. The thermal expansion means reduces expansion/contraction forces on the insulation system during heating from/cooling to cryogenic temperatures. If the space is filled with compressible material, the latter can be made semiconducting to ensure electrical contact between the semiconducting inner layer and the conducting means.

Other designs of conducting means are possible, the invention being directed to high voltage rotating electric machines having at least one winding formed of cooled electrically conducting means, preferably comprising cooled superconducting means of any suitable design having a surrounding electrical insulation of the type described above. The plastics materials of the electrical insulation ensure that the winding can be flexed to a desired shape or form at least when at ambient temperatures. At cryogenic temperatures, the plastics materials are generally rigid. However the winding can be made into a desired form within the stator/rotor slots at ambient temperatures before cryogenic cooling fluids are used to cool the conducting means.

Preferably the adjoining electrical insulation layers should have essentially the same coefficients of thermal expansion. At temperature gradients, defects caused by different temperature expansion in the insulation and the surrounding layers should not arise. The electric load on the material decreases as a consequence of the fact that the semiconducting layers around the insulation will constitute equipotential surfaces and that the electrical field in the insulating part will be distributed relatively evenly over the thickness of the insulation.

The outer layer may be cut off at suitable locations along the length of the cable and each cut-off partial length may be directly connected to a chosen electric potential.

Other knowledge gained in connection with the present invention is that increased voltage load leads to problems with electric field (E) concentrations at the corners at a cross section of a coil and that this entails large local loads on the electrical insulation there. Likewise, the magnetic field (B) in the teeth of the stator will, in the case of increased current load, be concentrated at the corners. This means that magnetic saturation arises locally and that the magnetic core is not utilized in full and that

the waveform of the generated voltage/current will be distorted. In addition, eddy-current losses caused by induced eddy currents in the conductors, which arise because of the geometry of the conductors in relation to the magnetic field B, will entail additional disadvantages in increasing current densities. A further improvement of the invention is achieved by making the coils and the slots in which the coils are placed essentially circular instead of rectangular. By making the cross section of the coils circular, these will be surrounded by a constant magnetic field B without concentrations where magnetic saturation may arise. Also the electric field E in the coil will be evenly distributed over the cross section of the electrical insulation and local loads on the electrical insulation are considerably reduced. In addition, it is easier to place circular coils in slots in such a way that the number of coil sides per coil group may increase and an increase of the voltage may take place without the current in the conductors having to be increased. The reason for this is that the cooling of the conductors is facilitated by, on the one hand, a lower current density and hence lower temperature gradients across the electrical insulation and, on the other hand, by the circular shape of the slots which entails a more uniform temperature distribution over a cross section.

An advantage of using a rotating electric machine according to the invention is that the machine can be operated at overload for a considerably longer period of time than is usual for such machines without being damaged. This is a consequence of the design of the machine and the limited thermal load of the electrical insulation. It is, for example, possible to load the machine with up to 100% overload for a period exceeding 15 minutes and up to two hours.

As synchronous compensators there are used, inter alia, synchronous motors without a connected mechanical load. By adapting the magnetisation, the synchronous condenser may give either inductive or capacitive kVA. When the compensator is

connected to a power network, it may compensate for inductive or capacitive load on the network within an interval. Since the synchronous compensator must be connected to certain power networks with voltages exceeding about 20 kV via a transformer, the range of the synchronous compensator within which it may provide the network with reactive power is influenced by the fact that the reactance of the transformer limits the angle of lag between current and voltage. With a rotating electric machine according to the invention, it is possible to design a synchronous compensator which may be connected to a power network without an intermediate transformer and which may be operated with a chosen under- or over-excitation to compensate for inductive or capacitive loads on the network.

A rotating electric machine according to the invention can be connected to one or more system voltage levels. This is possible because the electric field outside the machine can be kept to a minimum.

The connection to different system voltage levels can be provided by having separate tappings on one winding or by having a separate winding for the connections to different system voltage levels or by combinations of these arrangements.

Preferably, cables with a circular cross section are used. Among other things, to obtain a better packing density, cables with a different cross section may be used. To build up a voltage in the rotating electric machine, the cable is arranged in several consecutive turns in slots in the magnetic core. The winding can be designed as a multi-layer concentric cable winding to reduce the number of end winding crossings. The cable may be made with tapered insulation to utilize the magnetic core in a better way, in which case the shape of the slots may be adapted to the tapered insulation of the winding.

A significant advantage of a rotating electrical machine according to the invention is that the electric field E is

near zero in the end winding region outside the semiconducting outer layer and that with the outside of the insulation at earth potential, the electric field need not be controlled. This means that no field concentrations can be obtained, neither within sheets, in end winding regions or in the transition in between.

The present invention also enables a winding to be manufactured by placing the winding in the slots by threading a cable into the openings in the slots in the magnetic core. Since the cable is flexible, it can be bent, prior to operation, e.g. at cryogenic temperatures, and this permits a cable length to be located in several turns in a coil. The end windings will then consist of bending zones in the cables. The cable may also be joined in such a way that its properties remain constant over the cable length. This method is considerably simpler than state of the art methods. The so-called Roebel bars are not flexible but must be preformed into the desired shape. Impregnation of the coils is also an exceedingly complicated and expensive technique when manufacturing rotating electric machines today.

Thus to sum up, a rotating electric machine according to the invention provides a considerable number of important advantages over corresponding prior art machines. Firstly, it can be connected directly to a power network at all types of high voltage. High voltage in this respect means voltages exceeding 10 kV and up to the voltage levels which occur for power networks, such as 400 kV to 800 kV or higher. Another important advantage is that a chosen potential, for example earth potential, is consistently conducted along the whole winding, which means that the end winding region can be made compact and that support means at the end winding region can be applied at practically ground potential or any other chosen potential. Still another important advantage is that oil-based insulation and cooling systems disappear. This means that no sealing problems may arise and that the dielectric ring previously mentioned is not needed. One advantage is

also that all forced cooling can be made at earth potential. A considerable space and weight saving from the installation point of view is obtained with a rotating electric machine according to the invention, since it replaces a previous installation design with both a machine and a step-up transformer. The invention preferably makes use of superconducting means. Since a step-up transformer can be avoided, the efficiency of the system is considerably increased.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention will now be described, by way of example only, with particular reference to the accompanying drawing, in which:

Figure 1 is a schematic sectional view of a cable used in a winding of a high voltage rotating electric machine according to the invention; and

Figure 2 is an axial end view of a sector/pole pitch of a magnetic circuit of a high voltage electric machine according to the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figure 1 shows one type of superconducting cable 2 for use in a winding of a high voltage rotating electric machine according to the present invention. The cable 2 comprises elongate inner superconducting means 3 and outer electrical insulation 4. The elongate inner superconducting means 3 comprises an inner metal, e.g. copper or highly resistive metal or alloy, support tube 31 and an HTS wire 32 wound helically around the tube 31 and embedded in a layer 33 of semiconducting plastics material. The electrical insulation 4 is arranged outwardly of, at a small radial spacing 34 from, the layer 33. This electrical insulation 4 is of unified form

and comprises an inner semiconducting layer 35, an outer semiconducting layer 36 and, sandwiched between these semiconducting layers, an insulating layer 37. The layers 35-37 preferably comprise thermoplastics materials which are preferably solidly connected to each other at their interfaces but which could be in close mechanical contact with each other. Conveniently these thermoplastics materials have similar coefficients of thermal expansion and are preferably extruded together around the inner superconducting means. Preferably the layers 35-37 are extruded together to provide a monolithic structure so as to minimise the risk of cavities and pores within the electrical insulation. The presence of such pores and cavities in the insulation is undesirable since it gives rise to corona discharge in the electrical insulation at high electric field strengths.

The semiconducting outer layer 36 is connected at spaced apart regions along its length to a controlled electric potential, e.g. earth or ground potential, the specific spacing apart of adjacent earthing points being dependent on the resistivity of the layer 36 although when placed in winding slots of a core the "earthing points" should be at the end winding at the end of the slots.

The semiconducting layer 36 acts as a static shield and as an "earthed" outer layer which ensures that the electric field of the superconducting cable is retained within the solid insulation between the semiconducting layers 35 and 36. Losses caused by induced voltages in the layer 36 are reduced by increasing the resistance of the layer 36. However, since the layer 36 must be at least of a certain minimum thickness, e.g. no less than 0.8 mm, the resistance can only be increased by selecting the material of the layer to have a relatively high resistivity. The resistivity cannot be increased too much, however, else the voltage of the layer 36 mid-way between two adjacent controlled voltage, e.g. earth, points will be too high with the associated risk of corona discharges occurring.

The radial spacing 34 provides an expansion/contraction gap to compensate for the differences in the thermal coefficients of expansion (α) between the electrical insulation 4 and the inner superconducting means 3 (including the metal tube 31). The spacing 34 may be a void space or may incorporate a foamed, highly compressible material to absorb any relative movement between the superconductor and insulation system. The foamed material, if provided, may be semiconductive to ensure electrical contact between the layers 33 and 35. Additionally or alternatively, metal wires may be provided for ensuring the necessary electrical contact between the layers 33 and 35.

The HTS wire 32 is cooled to cryogenic temperatures by the passage of a cooling fluid, e.g. liquid nitrogen, through the tube 31.

By way of example only the semiconducting plastics material of each of the layers 33, 35 and 36 may comprise, for example, a base polymer, such as ethylene-propylene copolymer rubber (EPR) or ethylene-propylene-diene monomer rubber (EPDM), and highly electrically conductive particles, e.g. particles of carbon black embedded in the base polymer. The volume resistivity of these semiconducting layers, typically about 20 ohm·cm, may be adjusted as required by varying the type and proportion of carbon black added to the base polymer. The following gives an example of the way in which volume resistivity can be varied using different types and quantities of carbon black.

Base Polymer	Carbon Black Type	Carbon Black Quantity (%)	Volume Resistivity Ω·cm
Ethylene vinyl acetate copolymer/ nitrite rubber	EC carbon black	~15	350-400
-"-	P-carbon black	~37	70-10
-"-	Extra conducting carbon black, type I	~35	40-50
-"-	Extra conducting black, type II	~33	30-60
Butyl grafted polyethylene	-"-	~25	7-10
Ethylene butyl acrylate copolymer	Acetylene carbon black	~35	40-50
-"-	P carbon black	~38	5-10
Ethylene propene rubber	Extra conducting carbon black	~35	200-400

The HTS wire 32 may suitably comprise a core of an alloy of superconducting material sheathed in an electrically conductive outer layer, e.g. of silver or silver alloy. Typical of such an HTS wire are silver-sheathed BSCCO-2212 or BSCCO-2223.

To optimise the performance of a rotating electric machine, the design of the magnetic circuit, and in particular the core slots and core teeth is of critical importance. As mentioned above, the slots should connect as closely as possible to the casing of the coil sides. It is also desirable that the teeth at each radial level are as wide as possible to minimise the losses in, the magnetization requirement, etc., of the machine.

Figure 2 shows an axial end view of a sector/pole pitch 6 of a rotating electric machine according to the invention. The rotor with the rotor pole is designated 7. In conventional manner, the stator is composed of a laminated core of sector-shaped laminations. From a yoke portion 8 of the core, located radially outermost, a number of teeth 9 extend radially inwards towards the rotor 7 with slots 10

formed between the teeth 9. Cables 1 are wound in the slots 10 to form windings in the slots. The use of such cables allows among other things the depth of the slots for high-voltage machines to be made larger than has been possible according to the state of the art. The slots conveniently each have a cross section which decreases, typically but necessarily, in steps or sections towards the rotor (i.e. the slots become narrower towards the rotor) since the need for cable insulation becomes less for each turn or layer of the winding positioned closer to the air gap between the rotor and the stator. As is clear from Figure 2, each slot in radial section substantially consists of spaced apart portions 12 of circular cross section in which the winding layers or turns are received and narrower waist portions 13 linking the portions 12. The slot cross section may be referred to as a "cycle chain slot". In the embodiment shown in Figure 2, cables with three different dimensions of the cable insulation are used, arranged in three correspondingly dimensioned sections 14, 15 and 16. Figure 2 illustrates that the stator teeth can be shaped with a practically constant width in the circumferential direction throughout the radial extent.

The cable 1 can be made in three different joined together sections for reception in the different slot sections 14, 15 and 16. Preferably adjacent cable sections are joined together at cable joints positioned outside, e.g. at one end of, a slot. Typically in a cable joint, the inner support tubes are welded together and the superconducting wire or tape wound therearound are joined together, e.g. by soldering. Typically the joint is surrounded by solid, void-free polymeric material, e.g. of similar polymeric material to that used for the electrical insulation.

The scope of the invention accommodates a large number of alternative embodiments, depending on the available cable dimensions as far as insulation and the outer semiconductor layer etc. are concerned. Also embodiments with so-called

cycle chain slots can be modified differently to what has been described above.

As mentioned above, the magnetic circuit may be located in the stator and/or the rotor of the rotating electric machine. However, the design of the magnetic circuit will largely correspond to the above description independently of whether the magnetic circuit is located in the stator and/or the rotor.

Each winding may preferably be described as a multilayer, concentric cable winding. Such a winding implies that the number of crossings at the end windings has been minimised by placing all the coils within the same group radially outside one another. This also permits a simpler method for the manufacture and the threading of the stator winding in the different slots.

Although the present invention is primarily directed to rotating machines having at least one winding with conducting means with superconducting properties which are cooled to superconducting temperatures in use, the invention is also intended to embrace rotating machines in which at least one of the windings has conducting means exhibiting improved electrical conductivity at a low operating temperature, up to, but preferably no more than, 200 K, but which may not possess superconducting properties at least at the intended low operating temperature. At these higher cryogenic temperatures, liquid carbon dioxide can be used for cooling the conducting means.

The invention is generally applicable to rotating electric machines for voltages exceeding 10 kV. Rotating electric machines according to what is described under the "Technical Field" are examples of rotating electric machines for which the invention is applicable.

The electrical insulation surrounding the inner conducting means of a winding of a high voltage rotating electric machine according to the invention is intended to be able to handle very high voltages and the consequent electric and thermal loads which may arise at these voltages. By way of example, such electric machines may have a rated power from a few hundred kVA up to more than 1000 MVA and with a rated voltages ranging from 3-4 kV up to very high transmission voltages of 400-800 kV. At high operating voltages, partial discharges, or PD, constitute a serious problem for known insulation systems. If cavities or pores are present in the insulation, internal corona discharge may arise whereby the insulating material is gradually degraded eventually leading to breakdown of the insulation. The electric load on the electrical insulation of a winding of a rotating electric machine according to the present invention is reduced by ensuring that the inner layer of the insulation is at substantially the same electric potential as the inner electrically conducting means and the outer layer of the insulation is at a controlled, e.g. earth, potential. Thus the electric field in the intermediate layer of insulating material between the inner and outer layers is distributed substantially uniformly over the thickness of the intermediate layer. Furthermore, by having materials with similar thermal properties and with few defects in the layers of the insulating material, the possibility of PD is reduced at a given operating voltages. The windings of the machine can thus be designed to withstand very high operating voltages, typically up to 800 kV or higher.

Although it is preferred that the electrical insulation surrounding the inner conducting means of a winding of a high voltage rotating electric machine according to the invention should be extruded in position, it is possible to build up an electrical insulation system from tightly wound, overlapping layers of film or sheet-like material. Both the semiconducting layers and the electrically insulating layer can be formed in this manner.

An insulation system can be made of an all-synthetic film with inner and outer semiconducting layers or portions made of polymeric thin film of, for example, PP, PET, LDPE or HDPE with embedded conducting particles, such as carbon black or metallic particles and with an insulating layer or portion between the semiconducting layers or portions.

For the lapped concept a sufficiently thin film will have butt gaps smaller than the so-called Paschen minima, thus rendering liquid impregnation unnecessary. A dry, wound multilayer thin film insulation has also good thermal properties and can be combined with a superconducting pipe as an electric conductor and have coolant, such as liquid nitrogen, pumped through the pipe.

Another example of an electrical insulation system is similar to a conventional cellulose based cable, where a thin cellulose based or synthetic paper or non-woven material is lap wound around a conductor. In this case the semiconducting layers, on either side of an insulating layer, can be made of cellulose paper or non-woven material made from fibres of insulating material and with conducting particles embedded. The insulating layer can be made from the same base material or another material can be used.

Another example of an insulation system is obtained by combining film and fibrous insulating material, either as a laminate or as co-lapped. An example of this insulation system is the commercially available so-called paper polypropylene laminate, PPLP, but several other combinations of film and fibrous parts are possible. In these systems various impregnations such as mineral oil or liquid nitrogen can be used.

In this specification "semiconducting material" means a substance which has a considerably lower conductivity than an electric conductor but which does not have such a low conductivity that it is an electric insulator. Suitably, but not essentially, the semiconducting material will have a resistivity of $1\text{-}10^5$ ohm·cm, preferably 10-500 ohm·cm and most preferably from 10 to 100 ohm·cm, typically 20 ohm·cm.